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Julian D. Maynard

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The goals of this project involve the development and application of new techniques in acoustics. The goals are: a) to study the properties of single crystal high temperature superconductor oxide materials with ultrasonic measurements; b) to study the properties of quasicrystals using ultrasound and acoustic analog systems; and c) to develop and apply a new resonant photo-acoustic technique to measure optical absorption in very low-loss glasses and crystals. Major accomplishments include the development of a new method of ultrasound measurement which permits the determination of all of the independent elastic constants of very small samples (a few hundred microns in size), and the development and test of a new technique for measuring optical absorption with more than an order of magnitude improvement in sensitivity over existing methods.

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UNCLASSIFIED

ACOUSTIC STUDIES OF NEW MATERIALS:

QUASICRYSTALS, LOW-LOSS GLASSES, AND HIGH Tc SUPERCONDUCTORS

This report summarizes the goals and accomplishments for ONR contract N00014-85-K-0701, Mod P0004, "Acoustic Studies of New Materials: Quasicrystals, Low-loss Glasses, and High T_c Superconductors." The goals of the project involve the development and application of new techniques in acoustics. The goals are: a) to study the properties of single crystal high temperature superconductor oxide materials with ultrasonic measurements; b) to study the properties of quasicrystals using ultrasound and acoustic analog systems; and c) to develop and apply a new resonant photoacoustic technique to measure optical absorption in very low-loss glasses and crystals. The report lists published papers, submitted papers, talks, etc., and technical progress. Major accomplishments include a rigorous test of the small sample resonant ultrasound technique for measuring all of the elastic constants of very small samples of superconductors and quasicrystals, initial measurements in an experiment to measure mode-locking in a nonlinear quasicrystal, and measurements of optical absorption in a very low loss optical material (a CaF_2 crystal) using our new resonant photoacoustic technique. A list of our publications, presentations, honors, etc., and a preprint of a paper describing the testing of the small sample ultrasound apparatus using oriented single crystals of quartz are presented in appendices.

Published papers, submitted papers, talks, etc.

A complete list of publications, talks, etc. is presented in Appendix I. To summarize, there were two invited review papers on our research with quasicrystals and acoustic holography, and five publications in refereed

journals, including three in the proceedings of a conference; three papers were submitted, including a chapter in a forthcoming edition of the Physical Acoustics series. An article featuring our quasicrystal research appeared on the front page of the New York Times Science Section (September 5, 1990). A number of invited talks describing our research were given: there were two colloquia at universities and one at a NASA laboratory, and there were four invited lectures national meetings; there were also six contributed papers.

A notable item for the past year is the number of Doctoral and Masters degrees which have been completed. The students, theses topics, and some comments are as follows:

1. Tania Slawecki completed a Masters thesis involving experiments with sound propagation through porous glasses (aerogels) filled with superfluid helium. She currently is working in a polymer research lab.
2. James Mather obtained a Masters degree based on his work in developing the small sample ultrasound apparatus. He is now studying aeroacoustics and hydrodynamics for application to meteorology.
3. Chang Yu obtained his Ph.D. for his work in developing the resonant photoacoustic technique. He is now in an industrial research lab, using surface waves to probe integrated circuits during fabrication.
4. Yanmin Huang obtained his Ph.D. with research involving the holographic reconstruction of sources with arbitrary shapes. He is currently at the Cleveland Clinic Foundation doing research on new medical imaging techniques.
5. Shanjin He completed a Ph.D. thesis describing his experiments with acoustic analogs of Anderson localization in a random system and eigenmodes of a quasiperiodic system. He has a position as a post-doc at U. Mass, Amherst, doing research with sound propagation in porous media (rocks, etc.)

Abstracts from the theses are presented in Appendix II.

While the graduation of these excellent students has been a loss for our lab, we have been fortunate in attracting new students and a post-doc who promise to be even better. Ph.D. candidate James White has taken over the resonant photoacoustic experiment, Masters candidate Doug Meegan is doing research with nonlinear effects in the acoustic analogs, and Ph.D. candidate Phil Spoor has taken over the small sample resonant ultrasound measurements. The progress which these students have made will be described in the next sections.

Research with the Resonant Photoacoustic Technique

The original test of the resonant photoacoustic technique involved measurements with a high quality (highly transparent) crystalline quartz sample. With this sample it was discovered that the dominant transduction mechanism was piezoelectric rather than dielectric. The transducer was an interdigital capacitor located in proximity to, but not touching, the sample; the motion of the (dielectric and possibly piezoelectric) sample due to the acoustic field could be detected by the change in the transducer capacitance due to the moving dielectric, or by the voltage induced by the fringing electric field of the piezoelectric sample. For the quartz sample the piezoelectric mechanism gave a relative large signal. For a complete test of the technique it would be necessary to use a sample material which was not so piezoelectric. For this purpose James White has performed measurements using a high quality (highly transparent) CaF_2 sample. The signal is approximately two orders of magnitude smaller, but the absorption coefficient of $\sim 10^{-4}$ cm^{-1} can still be measured.

In order to measure even smaller optical absorption coefficients, it is necessary to use a high power infrared laser. An equipment proposal for such a laser and related equipment was submitted to ONR and approved. The laser was

ordered and recently received; the associated optics and computer equipment is on order. Measurements in the more transparent infrared region should begin soon.

Research with Linear and Nonlinear Acoustic Analogs

Studies of the effects of linear wave propagation in one-dimensional random systems have been pursued with some computer simulations which allow studies under much more diverse conditions than permitted with the mass-loaded wire experiment. The purpose was to explore the relevance of many of the theoretical statements which are made in regard to solid state systems. It was found that many of the statements are misleading. The problem is that the theory is limited tc ensemble averages, while measurements are made on single realizations of a system, and there is no "ergotic theorem" for these effects. Another problem is that it is sometimes overlooked that Bloch waves are not real waves; they do not carry momentum and energy like real waves, and the fact that frequencies and wavenumbers must be equal does not mean that "energy" and "momentum" are being conserved. In fact is possible for a Bloch wave traveling in one direction to carry energy in the opposite direction. While theoreticians in solid state know this, semantics used for expedience have often led to confusion.

Experiments on nonlinear effects in the mass-loaded wire have been initiated. We have observed that for finite amplitude transverse waves, the arc length of the displaced wire is increased over the length of the equilibrium (straight) wire with the result that the tension in the wire is modulated. At sufficiently large amplitudes, the modulated tension in the wire parametrically excites other modes, with dramatic results. Results have been reported at the Acoustical Society meeting at Penn State University and at the ONR Principal Investigator meeting in Monterey. The nonlinear research will

be pursued for a random system. A new type of experiment on mode-locking in a quasicrystalline system is being designed.

Research with the Small Sample Resonant Ultrasound Technique

Single crystal samples of high temperature superconductors have been promised by our collaborators at Los Alamos, but as yet we have received none. Other sources of samples have been pursued. We have also been promised a high quality sample of an aluminum alloy quasicrystal from Brage Golding at AT&T Bell Labs, and this sample is being prepared. We have also just received some small (500-800 μm diameter) ceramic bead samples, referred to as "proppants", of various composition from John Hellmann of the Center for Advanced Materials at Penn State; Phil Spoor is initiating measurements of the elastic constants for these samples.

While waiting for samples, Phil Spoor undertook a rigorous test of the small sample resonant ultrasound technique, using an oriented single crystal of quartz. Our measured elastic constants were in good agreement with the reported constants for quartz (although there is some spread in the tabulated values); however, our sample was considerably smaller than any of the others used for measurements by the traditional ultrasonic pulse-echo technique. In the course of the testing we developed improved computer algorithms for inverting the measured acoustic spectrum to obtain the elastic constants. A paper describing this research has been submitted to the J. Acoust. Soc. Amer.; the abstract for this paper is presented in Appendix III.

Current and Other Funding

It is anticipated that there will be no remaining funds at the end of the contract period.

Other research grants include NSF Division of Materials Research, Low Temperature Physics Program, DMR 9000549, which includes 2 man-months of the principal investigators time.

APPENDIX I

OFFICE OF NAVAL RESEARCH

PUBLICATIONS / PATENTS / PRESENTATIONS / HONORS REPORT

FOR 1 OCTOBER 1989 through 30 SEPTEMBER 1990

****

CONTRACT N00014-85-K-0701

ACOUSTIC STUDIES OF NEW MATERIALS: QUASICRYSTALS, LOW LOSS GLASSES, AND HIGH Tc SUPERCONDUCTORS

Julian D. Maynard

Department of Physics

The Pennsylvania State University

University Park, Pa 16802

****

PAPERS SUBMITTED TO REFEREED JOURNALS
(Not yet published)

1. J. D. Maynard, "Using Piezoelectric Film and Acoustic Resonance to Determine the Complete Elastic Tensor in One Measurement", submitted to the J. Acoust. Soc. Am.

2. J. D. Maynard, "Tuning-up a Quasicrystal", Proceedings of the Summer Seminar on Mathematics of Random Media, ed B. White

3. J. D. Maynard, "Solving quantum mechanical puzzles with acoustic analogs" submitted to the Amer. J. Phys.

PAPERS PUBLISHED IN REFEREED JOURNALS

1. J. D. Maynard, "Effects of quasiperiodic (Penrose tile) symmetry on the eigenvalues and eigenfunctions of the wave equation", IBM Journal of Research and Development 33, 456-463 (1989)

2. A. Migliori, W. M. Visscher, S. E. Brown, Z. Fisk, S-W. Cheong, F. M. Mueller, B. Alten, E. T. Ahrens, K. A. Martin (Los Alamos National Labs), J. D. Maynard, M. H. W. Chan, Y. Huang, and D. Kirk (Penn State University) "Low temperature elastic constant and specific heat anomolies in single crystal La_2CuO_4", Phys. Rev. B 41, 2098 (1990)

3. T. P. Brosius, M. J. McKenna, and J. D. Maynard, "Evidence for quantum kinks in the layer-by-layer growth of solid helium on graphite", Proceedings of the Nineteenth International Conference on Low Temperature Physics, ed. D. Brewer

4. M. J. McKenna, Tania M. Slawecki, and J. D. Maynard, "Second and fourth sound modes for superfluid helium in aerogel", Proceedings of the Nineteenth International Conference on Low Temperature Physics, ed. D. Brewer

5. M. J. McKenna, R. J. Stanley, Elaine DiMasi, and J. D. Maynard, "Observation of soliton-like waves in adsorbed films of superfluid 4He" Proceedings of the Nineteenth International Conference on Low Temperature Physics, ed. D. Brewer

PAPERS PUBLISHED IN NON-REFEREED JOURNALS

TECHNICAL REPORTS PUBLISHED

1. NSF Final Progress Report

2. Tania Slawecki M.S. Thesis "Measuring fourth sound in silica aerogel"

3. Chang Yu Ph.D. Thesis "A high Q resonant photoacoustic technique for small optical absorption measurements"

4. Yanmin Huang Ph.D. Thesis "Computer techniques for three-dimensional source radiation"

5. J. A. Mather M.S. Thesis "A New Technique for Ultrasound Measurement in Very Small Samples with Applications to Aluminum Alloy Quasicrystals"

6. Shanjin He Ph.D. Thesis "Acoustic analog experimental study of the physical properties of one dimensional disordered systems and two-dimensional quasiperiodic systems"

BOOKS (AND SECTIONS THEREOF) SUBMITTED FOR PUBLICATIONS

1. J. D. Maynard, A. Migliori, and W. M. Visscher, "Ultrasonic measurements of elastic constants in single crystals of La_2CuO_4", to be published as a chapter in Ultrasonics of High-Tc and Other Unconventional Superconductors, ed. Moises Levy

BOOKS (AND SECTIONS THEREOF) PUBLISHED

INVITED PRESENTATION AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. Invited Lecture, IEEE Ultrasonics Symposium, October 1989, Montreal
   "Analog simulations of acoustic localization"

2. Invited Lecture, 1990 AAPT/APS Joint Meeting, Atlanta, GA, January 1990
   "Classical acoustics solves quantum mechanical puzzles"

3. Invited Lecture, National Meeting of the American Association for the Advancement of Science, February 1990, New Orleans
   "Classical acoustics solves quantum mechanical puzzles"

4. Invited lecture (with David Blackstock) 119th Meeting of the Acoustical Society of America, State College, May 1990
   "Demonstration of nonlinear acoustics phenomena"

5. Colloquium, Department of Physics, University of Houston, October 1989
   "Tuning-up a quasicrystal"

6. Seminar, Exxon research and Engineering Company, November 1989
   "Acoustic Anderson localization"

7. Colloquium, Department of Physics, Kent State University, February 1990
   "Tuning-up a quasicrystal"

8. Colloquium, NASA Goddard Space Flight Center, March 1990
   "Quasicrystals and impossible forms of matter"

CONTRIBUTED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. C. Yu and J. D. Maynard, 118th Meeting of the Acoustical Society of America, St. Louis, November 1989, "A new resonant photoacoustic technique for measuring very low optical absorption in glasses"

2. J. D. Maynard and C. Yu, 118th Meeting of the Acoustical Society of America, St. Louis, November 1989, "The use of reciprocity to calibrate a resonant photoacoustic measurement"

3. T. M. Slawecki, M. J. McKenna, and J. D. Maynard, "Measurements of high frequency fourth sound in low density aerogel", Bull. Am. Phys. Soc. 35, 1027 (1990)

4. T. B. Brosius, M. J. McKenna, and J. D. Maynard, "Observation of bimodal nucleation in epitaxial growth below a second roughening transition for 4He", Bull. Am. Phys. Soc. 35, 1027 (1990)

5. J. D. Maynard, M. J. McKenna, P. S. Spoor, and R. L. Stanley, "Studies of non-linear effects in third sound propagation; Observation of soliton behavior", Bull. Am. Phys. Soc. 35, 1027 (1990)

6. M. J. McKenna, P. S. Spoor, R. L. Stanley, and J. D. Maynard, "Experiments on linear and nonlinear wave propagation in random and quasiperiodic media" 119th Meeting of the Acoustical Society of America, State College, May 1990

HONORS/AWARDS/PRIZES

Elected Fellow of the American Physical Society, November 12, 1989

An article featuring our research on quasicrystals appeared on the front page of the New York Times science Section, September 5, 1989.

GRADUATE STUDENTS SUPPORTED UNDER CONTRACT FOR YEAR ENDING 30 SEPTEMBER 1990

1. Yanmin Huang (Ph.D. candidate, physics) [Summer support]
   Computer Techniques for Unbaffled Source Radiation

2. Shanjin He (Ph.D. candidate, physics) [Summer support]
   Acoustic Anderson Localization

3. Chang Yu (Ph.D. candidate, physics)
   Acousto-optic Resonance

4. Philip Spoor (Ph.D. candidate, acoustics)
   Elastic Constants for Aluminum Alloy Quasicrystals and High Tc Superconductors

5. Doug Meegan (M.S. candidate, physics)
   Nonlinear effects in Random and Quasiperiodic Systems

6. James White (Ph.D. candidate, physics)
   Infrared Resonant Photoacoustic Technique

POSTDOCTORALS SUPPORTED UNDER CONTRACT FOR YEAR ENDING 30 SEPTEMBER 1990

Mark McKenna, Research Associate, began July 1, 1989

APPENDIX II

The Pennsylvania State University

The Graduate School

Department of Physics

Measuring Fourth Sound in Silica Aerogel

A Thesis in

Physics

by

Tania Maria Slawecki

Submitted in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science

December 1989

Abstract
Measuring Fourth Sound in Silica Aerogel
Tania Maria Slawecki
M.S.; December 1989
The Pennsylvania State University
Julian D. Maynard, Jr., Thesis Advisor

The properties of superfluid ^{4}He are well documented so that it becomes convenient to use this non-viscous liquid to probe the structure of porous media. The recent development of aerogels introduces a new porous material whose interesting properties directly relate to their microstructures. Measuring fourth sound in silica aerogel reveals a definite deviation in the fourth sound speed and attentuation as a function of temperature. This difference is attributed to the scattering correction n, which is directly related to the geometry of the silica network. However, n is also found to vary with temperature. This deviation may be due to the high compressibility of the aerogel, which no longer acts as a rigid frame for clamping the normal fluid component.

The Pennsylvania State University

The Graduate School

Department of Physics

A New Technique for Ultrasound Measurement in Very Small Samples with Applications to Aluminum Alloy Quasicrystals

A Paper in Physics

by James H. Mather

Submitted in Partial Fulfillment
of the Requirements
for the degree of

Master of Science

May 1990

ABSTRACT

Well developed ultrasonic techniques exist for measuring acoustic properties of macroscopic samples. Recently, however, a number of interesting materials have been discovered which are only available in the form of very small samples. Of particular interest here is the quasicrystal. The largest pure quasicrystalline samples to date are only on the order of a few hundred microns in diameter. We have developed an ultrasonic resonance technique to study the acoustic properties of these small samples using a polymer piezoelectric film called polyvinylidene fluoride (PVDF). We have also worked with preparing the samples and have taken some preliminary data with the ultrasonic apparatus on $T_2(Al_6CuLi_3)$ (a quasicrystalline material) as well as on quartz.

The Pennsylvania State University

The Graduate School

Graduate Program in Physics

A High Q Resonant Photoacoustic Technique for Small Optical Absorption Measurements

A Thesis in

Physics

by

Chang Yu

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

ABSTRACT

A new photoacoustic (PA) technique has been developed for measuring small optical absorption in highly transparent materials. In this new technique, the laser intensity is modulated at the acoustic resonant frequency of the solid sample, to obtain an enhanced PA signal and therefore an improved measurement sensitivity.

Experiments testing this new technique were carried out on crystalline quartz (SiO_2) samples having ~ centimeter dimensions. A significant amplification of the PA signal proportional to Q (quality factor) is observed when the laser intensity is modulated at the resonant frequency (~ 10^5 Hz) of tne quartz sample. To increase the Q and thus increase the sensitivity, the measurements are carried out in vacuum, the sample supports are located at nodal lines of the resonance with computer controlled positioners, and the transducers are non-contact interdigital capacitors fabricated by a photolithography technique. The best Q thus obtained was close to one million (0.84×10^6).

The non-contact transducers not only eliminate the problem of background signals due to scattered light, they also allow measurements on a sample without requiring any modification of or attachment to the sample.

At a CW laser power of ~ 1W and wavelength of 514.5 nm, a PA signal as high as 50 μV was obtained at the sample resonance with a signal-to-noise ratio of 1000, for an

absorbed optical energy of 10^{-10} J per cycle. The optical absorption coefficients of the quartz samples have been determined by this PA technique.

To explore the possibility of further improvements in the measurement sensitivity, multiple laser beam pass experiments have been performed and the PA signal was found to increase significantly with the increasing number of laser beam passes.

The Pennsylvania State University

The Graduate School

Department of Physics

COMPUTER TECHNIQUES FOR THREE-DIMENSIONAL SOURCE RADIATION

A Thesis in

Physics

by

Yanmin Huang

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

May 1990

ABSTRACT

A zoom imaging computer algorithm is presented, which can be used to compute the directivity of far-field radiation. Test cases demonstrate the success of this algorithm.

The Helmholtz Integral Equation method to compute the acoustical radiation of a three-dimensional source with arbitrary shape is reviewed. A numerical method to solve the Helmholtz Integral Equation using the finite element method is discussed. Second order interpolation functions, usually called shape functions, are used and they result in better accuracy and time saving in input data entry. Solutions for spherical monopole and dipole sources are compared to the theoretical results and agree well.

A new equivalent surface source method which is based on the Helmholtz Integral Equation is developed. It gives improved accuracy and can be used to compute the field of high frequency sources as well.

The Singular Value Decomposition (SVD) method is employed in these computer techniques. The uniqueness problem related to the surface Helmholtz Integral Equation can be monitored, and SVD can also be used to compute the eigenvalues of the corresponding interior problem. Some test results are presented.

The singular value decomposition method coupled with the finite element method implementation of Helmholtz Integral Equation enabled us to extend the near-field acoustical holography technique from two-dimensional to three-dimensional sources. Hence enabled us to reconstruct the motion on the surface of three-dimensional source from the measured acoustical field.

Reconstruction from numerical test case and near-field acoustical holography experiments are presented. The results are in good agreements with theoretical predictions.

The Pennsylvania State University

The Graduate School

Department of Physics

Acoustic Analog Experimental Study of Effects of Anderson Localization in One Dimension and Physical Properties of Two Dimensional Quasiperiodic Systems

A Thesis in

Physics

by

Shanjin He

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

August 1990

ABSTRACT

In this thesis, experimental study of the effects of Anderson localization in a one-dimensional random system and of physical properties of a two-dimensional quasiperiodic system by using acoustic analog techniques is reported.

The acoustic simulation experiment of Anderson Localization involves a one-dimensional wave medium consisting of a long steel wire. The wave field analogous to the electron Schrodinger wave consists of transverse waves in the wire generated with an electromechanical actuator. The Bloch-wave behavior is verified with the masses spaced periodically. In the study of localization effects, the positions of the masses are varied. Several sets of measurements are made with the positions randomly varied within maximum displacements from lattice sites of 1%, 2%, and 5% of the lattice constant.

Inelastic scattering effects in the localization problems is studied with 2% spacing disorder. In this investigation, two eigenstates are selected as an initial state and a final state. The transverse actuator is driven at the initial-state eigenfrequency, and a longitudinal actuator is driven at the frequency for resonant phonon-assisted hopping. The response of the system is then measured as a function of the amplitude of the longitudinal strain modulation amplitude. The measured hopping probability as a function of the longitudinal drive amplitude is obtained.

The acoustic simulation experiment to investigate the physical

properties of quasicrystals involved coupled oscillators in a two dimensional Penrose lattice. The tight-binding model is used and the tuning forks mounted at the centers of the rhombuses of the Penrose tile as local oscillators are nearest-neighbor-coupled together with arcs of steel wire connecting the tines of neighboring tuning forks. The oscillations of the system is driven by an electromagnet. The responses of the system is monitored by electrodynamic transducers. The eigenvalue spectrum, determined as a composite of the resonant spectra from 20 different positions in the Penrose pattern, shows a feature resulting from the quasiperiodic symmetry: the spectrum has gaps and bands whose widths are in the ratio of the Golden Mean $(\sqrt{5}+1)/2$. The eigenfunctions of the system are obtained which show the motions of the quasiperiodic oscillator system (both amplitude and polarization) at eigenfrequencies.

APPENDIX III

Using Piezoelectric Film and Ultrasound Resonance to Determine the Complete Elastic Tensor in One Measurement

J. D. Maynard

Department of Physics

The Pennsylvania State University, University Park, PA 16802

The ultrasonic and elastic properties of materials are conventionally measured using quartz, lithium niobate, etc. transducers and a pulse-echo technique with the transducer driven at resonance. Problems with the technique include transducer ringing, coupling, parallelism of sample faces, beam diffraction, and the necessity of remounting transducers in order to measure all of the elastic constants. Usually these problems can be minimized, but with samples which are only a fraction of a millimeter in size, conventional ultrasound measurements become difficult if not impossible. However, nearly all of these problems disappear if a resonance technique is used, and all of the elastic constants may be determined with a single measurement. For the broadband response and minimum transducer loading required for a resonance measurement in a small sample, polyvinylidene flouride (PVDF) piezoelectric film (as thin as 9 μm) is ideally suitable.